FIRE RISK ASSESSMENT FOR CHEMICAL STOCKPILE DISPOSAL PROGRAM FACILITIES

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ABSTRACT

The U.S. stockpile of chemical munitions stored at various locations in the Continental United States (CONUS) is scheduled to be thermally demilitarized under the supervision of the U.S. Army Chemical Stockpile Disposal Program (CSDP). This paper describes a fire risk assessment (FRA) performed under the system hazard analysis (SHA) task for the initial CSDP facility. The fire risk methodology used in the assessment is adopted from the methodology developed for nuclear power plant fire risk assessment. The task of fire risk assessment consists of three phases: (1) preparation, (2) fire risk assessment, and (3) fire risk management. Design recommendations were formulated based on the findings of the FRA to reduce the fire-induced risk and to improve safety-system reliability. The FRA presented in this paper proved to be a very useful tool in supporting the facility fire protection system design. It is also proved to be an important portion of the system hazard analysis task to assess the potential of agent release and equipment damage from fire.

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1. INTRODUCTION

1.1 BACKGROUND

The U.S. Department of Defense (DOD) has been directed by Congress in the DOD Authorization Act of 1986 (as amended by Public Law 100-456) to destroy the nation's stockpile of lethal unitary chemical warfare agents and munitions. The stockpile consists of nerve agents (GB and VX) and a blister agent (H/HD/HT, or mustard) in bulk storage containers, bombs, rockets, mines, projectiles, and mortar rounds stored at eight locations in the Continental United States (CONUS), in Europe, and at Johnston Atoll in the Pacific Ocean.

Because of the hazards associated with handling of these lethal unitary chemical warfare agents and munitions, Congress directed that the destruction be accomplished in such a manner as to provide: (1) maximum protection of the environment, the general public, and the personnel who will be involved in the demilitarization operations; (2) adequate and safe facilities designed solely for the destruction of the lethal chemical stockpile; and (3) cleanup, dismantling, and disposal of the facilities (i.e., decommissioning) when the disposal program is complete. Early in the CSDP, a System Safety Program Plan (SSPP) [Ref. 1] was developed to ensure that all of the project safety goals would be met in the various project stages, including design, construction, and testing. The system hazard analysis (SHA), is one of the key elements in the SSPP during the final design stage of the program.

A fire can either cause an accident or reduce the plant's margin of safety. A fire can damage equipment which is needed to safely operate the demilitarization processes and to prevent release of agent vapor from toxic areas during normal or abnormal operations. Apart from hardware failure, crucial equipment in the facility can also be damaged by fire, flooding, or other causes. Recent risk studies [Refs. 2 through 4] have concluded that fires can be important contributors to public health risk. The adverse effects of fire on plant safety are further demonstrated by the well-known cable-spreading-room fire at Browns Ferry Nuclear Power Plant [Ref. 5]. Therefore, fires present a substantial risk to the system safety; a fire risk assessment was performed for a CSDP facility as a part of the SHA to meet the SSPP requirement.

1.2 FIRE RISK ASSESSMENT

Investigation of fire risk requires the application of probabilistic risk assessment (PRA) technology to qualitatively and quantitatively assess the probability of fire occurrence rate, fire protection system (FPS) unavailability, and fire induced damage probability.

The key segments in the FRA are: assess fire frequency, evaluate fire damage probability, assign Risk Assessment Codes (RAC) to current design, and provide risk management recommendations. Event-tree/fault-tree methodology is applied to determine the probability of occurrence for the selected accident scenarios. Consequences of the accident scenarios are assessed via the loss of critical safety equipment and the estimate of agent release.

2. TECHNICAL APPROACH

The FRA adapts the general methodology that has been developed for fire risk assessments performed for nuclear power plants. The methodology combines engineering judgment, statistical evidence, fire phenomenology, and plant system analysis to systematically quantify the risk of fires to the operation in the facility.

2.1 OVERALL PLAN OF APPROACH

The overall approach for the FRA work is illustrated in Figure 2-1. The figure identifies the three main phases of the analysis, each of which involves several work activities:

Phase 1: Preparation: (a) plant design familiarization, (b) identification of engineered safety functions (ESFs), and (c) database development.

Phase 2: Fire Risk Assessment: (a) identification of critical locations and components and credible fire scenarios, (b) estimation of fire frequency, (c) estimation of fire-growth times and competing fire-detection and suppression time, (d) assessment of FPS unavailability, (e) assessment of fire-induced damage probability, and (f) evaluation of total fire risk.

Phase 3: Fire Risk Management: (a) design confirmation, and (b) fire risk reduction recommendations.

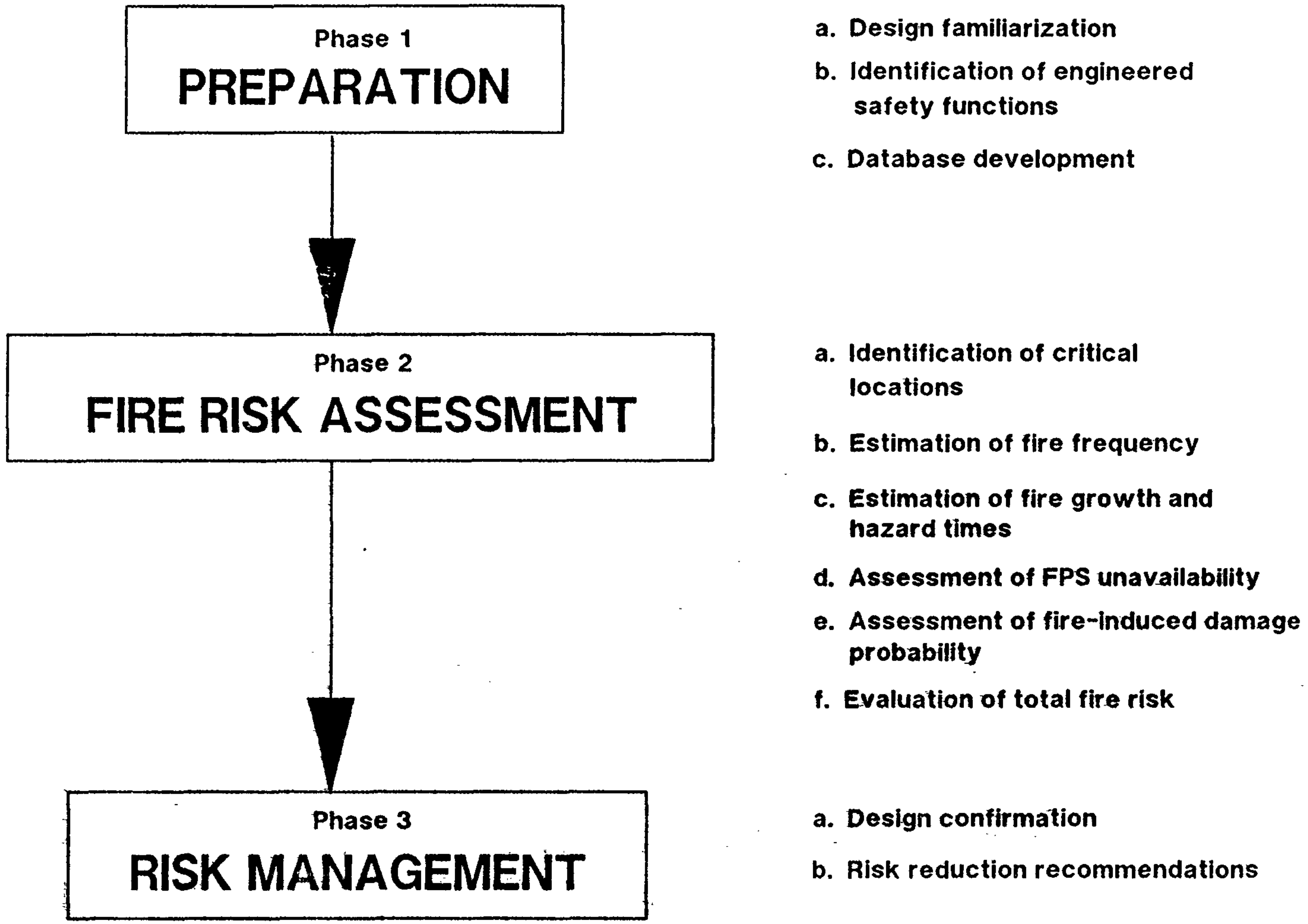

Figure 2-1 - Overall Approach of the FRA

2.2 PREPARATION

The occurrence of fires and their effects on the facility plant safety are very complex issues that require detailed design information. Documentation such as plant layout drawings, process flow diagrams (PFDs), piping and instrumentation diagrams (P&IDs), system descriptions, technical specifications, and other supporting engineering calculations was collected during the initial phase of the FRA. During this preparation phase, engineers from various disciplines - design, process instrumentation and fire protection - were consulted for correct interpretation of the drawings and processes.

Theoretically, an FRA should study all the potential contributors to the risk of agent release associated with fires anywhere in the facility. By screening out less important scenarios, however, the amount of work required can be greatly reduced without sacrificing significant confidence in the results. To accomplish this objective, a screening criterion is used to select only the fire scenarios that can damage engineered safety functions (ESF). An ESF is a safeguard designed to prevent agent from contaminating the nontoxic areas or to mitigate agent-release accidents. ESFs were identified from the PFDs, P&IDs, SHA [Ref. 6], and design criteria document. The identification of the ESFs sets forth the scope of the FRA and is an important step in the identification of critical locations analyzed in the following phases of the FRA.

2.3 FIRE RISK ASSESSMENT

A general methodology [Refs. 7 through 12] for the assessment of the risk associated with fires has been developed and applied in major PRAs [Refs. 13 through 16]. The methodology addresses many aspects of a fire incident (e.g., fire ignition, progression, detection and suppression, or characteristics of materials under fire conditions) as well as the plant safety functions and their behavior under accident conditions. Although the methodology was developed primarily for the evaluation of a nuclear power plant's fire risks, it can be applied to any complex facility.

2.3.1 Identification of Critical Locations and Components

A location is classified as critical when the occurrence of a fire there has the potential of creating an abnormal condition leading to the damage of the components that perform the ESFs (generally known as critical components) directly or indirectly. The critical locations are identified systematically by dividing the facility into fire areas. A fire area is defined as an area bounded by firewalls. Partitions separated from each other by non-fire-rated walls within a fire area are defined as a compartment. Compartments within a fire area are usually grouped into fire zones. The compartments within a fire zone are usually protected by the same FPS. If the FPS for a fire zone is lost, the fire-control capability is said to be lost in all compartments within the same zone. The critical locations analyzed were selected from these compartments based on the amount of hazardous material and combustibles available in the locations, the significance of the critical ESF equipment within the room, the consequences of losing this equipment, and the likelihood of fire initiation and propagation.

2.3.2 Definition of Fire Scenarios

Fire scenarios in each of the critical locations were postulated in order to conduct the risk analysis. These scenarios include different sizes of fires at the worst-case locations. A worst-case location is that where a fire can cause the most significant damage to the ESF equipment. Generally, a scenario includes the following information: the size of the fire, the location of the fire, the type of FPS, the equipment (target) being considered, and the progression of the fire event. The progression of a fire event is illustrated in Figure 2-2. Three events are included: (1) the automatic FPS is available, (2) fire is controlled successfully by automatic FPS, and (3) fire is controlled successfully by manual suppression. The first event models the reliability of the FPS, if present. The second event models the speed of the FPS, and the third event models the speed of the manual-suppression effort. The fire event will lead to a damage state by either of the following scenarios:

(1) The automatic FPS is fully functional as designed; however, the FPS cannot control the fire before the fire damages the ESF equipment.

(2) The automatic FPS is not functioning, or there is no automatic fire-suppression system installed in the compartment. Manual-suppression effort is not able to control the fire before damage occurs.

2.3.3 Fire Occurrence Frequency

Since fire occurrence data for facilities similar to the CSDP operation do not exist, available industrial fire experience and engineering judgment were used to approximate the frequency of occurrence of fires in the critical locations. A methodology that allows such an approach is formulated in References 7 and 17 through 21. The methodology integrates new evidence (including

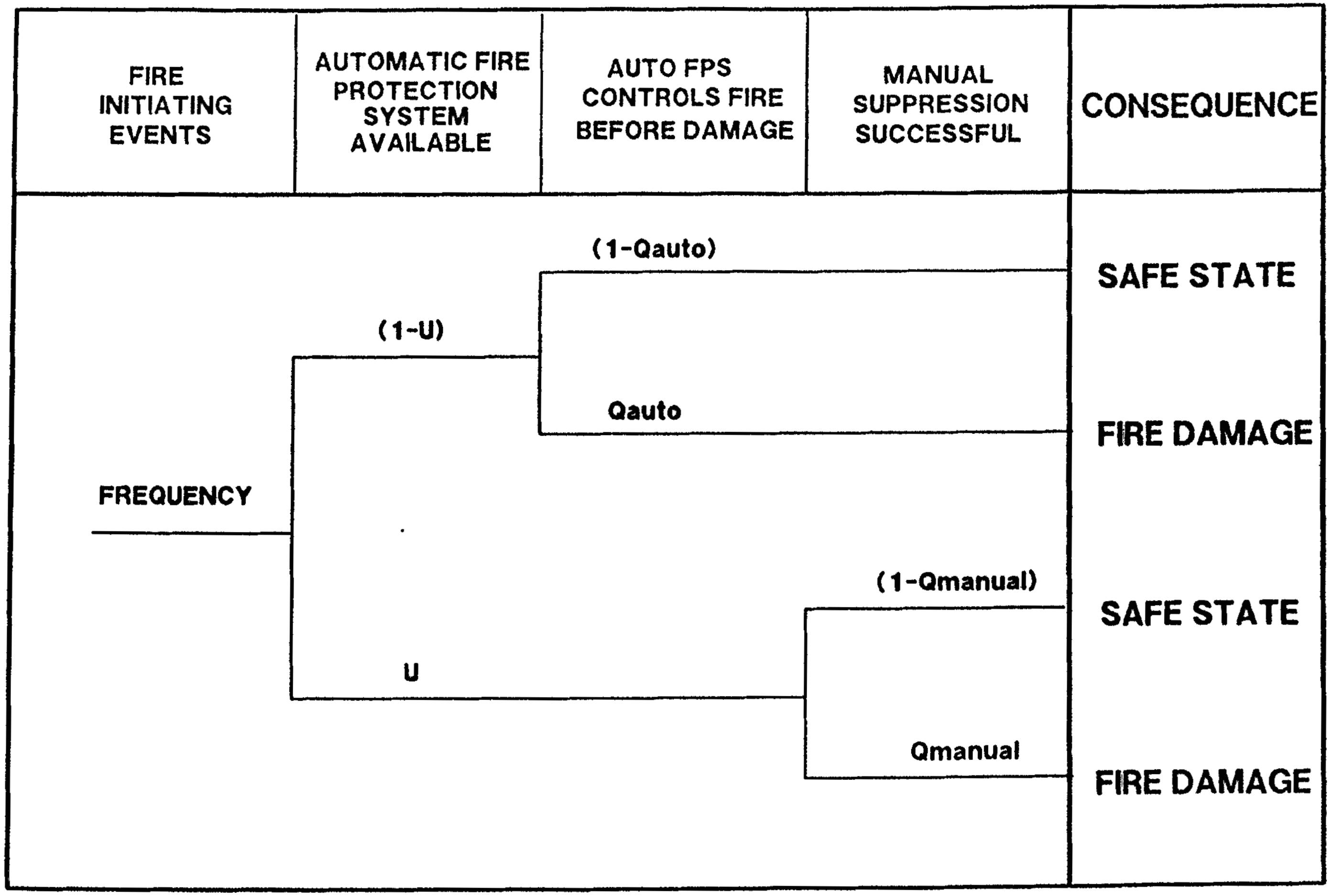

Figure 2-2 - Fire Event Tree Used in the FRA (Typical) imprecise or debatable evidence) into the state of knowledge of the frequency of fire occurrence. The central conceptual tool is Bayes' Theorem from the theory of probability. This theorem, the fundamental law of logical inference, is the ideal tool for quantitatively assessing the significance of various items and forms of information. Bayes' Theorem is expressed as follows:

$$K(a|E) = \frac{K_o(a) * L(E|a)}{\int_o^{\infty} K_o(a) * L(E|a)\, da} \qquad (2\text{-}1)$$

where

- $K_o(a)$ = probability distribution of the frequency "a" prior to having evidence E (prior distribution).
- $L(E|a)$ = likelihood function (probability of the evidence given a).
- $K(a|E)$ = probability density function of a given evidence (the posterior distribution).

In the FRA, the frequency of fires is treated as a random variable, and its distribution expresses our current state of knowledge about the values of that frequency. The prior distributions developed in the knowledge process are generic. Since there are no historical data of fire occurrence at the new facility, the prior distribution of the frequency for each of the critical locations is almost noninformative, i.e., no significant prior knowledge was injected into the analysis. The evidence used in the analysis was derived from actual nuclear power plant fire incidents as reported to the American Nuclear Insurers (see Table 2-1). Bayes' Theorem was used to formally incorporate the experience into the knowledge of the frequencies.

Based on the form of data available, the evidence (Table 2-1) is best modeled as a Poisson process. Therefore, the likelihood function is

$$L(E|a) = e^{-a\,T} \frac{(a\,T)^r}{r\,!} \qquad (2\text{-}2)$$

where

- a = frequency of occurrence used to model the process.
- T = number of relevant years of operation.
- r = number of fires.

Table 2-1 - Statistical Evidence of Fires in Light Water Reactors (As of June 1985) [Ref. 21]

Area	Number of Fires (r)	Number of Compartment Years (T)
Control Room	3	681.0
Cable Spreading Room	2	747.3
Diesel Generator Room	37	1600.0
Reactor Building	15	847.5
Turbine Building	21	654.2
Auxiliary Building	43	673.2
Electrical Switchgear Room	4	1346.4
Battery Room	4	1346.4

To facilitate the calculation, the gamma family of distributions, which is conjugate to the Poisson distributions, was chosen to represent the prior distribution. A gamma distribution is expressed as:

$$G(a) = \frac{b^{\alpha} * a^{\alpha-1} * e^{-b\,a}}{\Gamma(\alpha)} \qquad (2\text{-}3)$$

where α and b are the parameters of the distribution.

For the noninformative prior distribution, the greatest ignorance is represented by setting "A" and "b" to a value of zero. In the FRA, slightly more conservative prior distributions (α and $b > 0$) were used to give more weight to the values of "a" in the neighborhood of one per compartment-year. The distributions cover a wide range of values to express our vague prior knowledge. Since the gamma distributions are conjugate with respect to the Poisson distribution, the posterior distributions are also gamma distributions, with parameters $\alpha' = \alpha + r$ and $b' = b + T$.

To express the large uncertainties in applying the generic distributions obtained from nuclear power plant experience as the evidence for the facility operation, these distributions were further broadened to express the uncertainties in the application of the knowledge [Ref. 19]. The degree of broadening depends on the differences between the nuclear experience and the new facility designs.

2.3.4 Fire Growth Time and Competing Fire-Detection and Suppression Time

Figure 2-3 depicts a simplified view of the interactions in a compartment fire as modeled in the FRA. A fire starts and releases energy to other contents in the room. This energy causes the gas pressure in the flame zone to rise. The products of combustion, with temperature higher than that of the environment, are driven upward by buoyancy forces. A hot, turbulent plume is generated and begins to rise. The upward momentum of the plume depends on the distance between the fire source and the ceiling, the fire strength, and the thermal stratification of the room. Along the axis of the plume, relatively quiescent air at ambient temperature is entrained into the plume and mixes with the plume gases as they continue their ascent toward the ceiling. As a

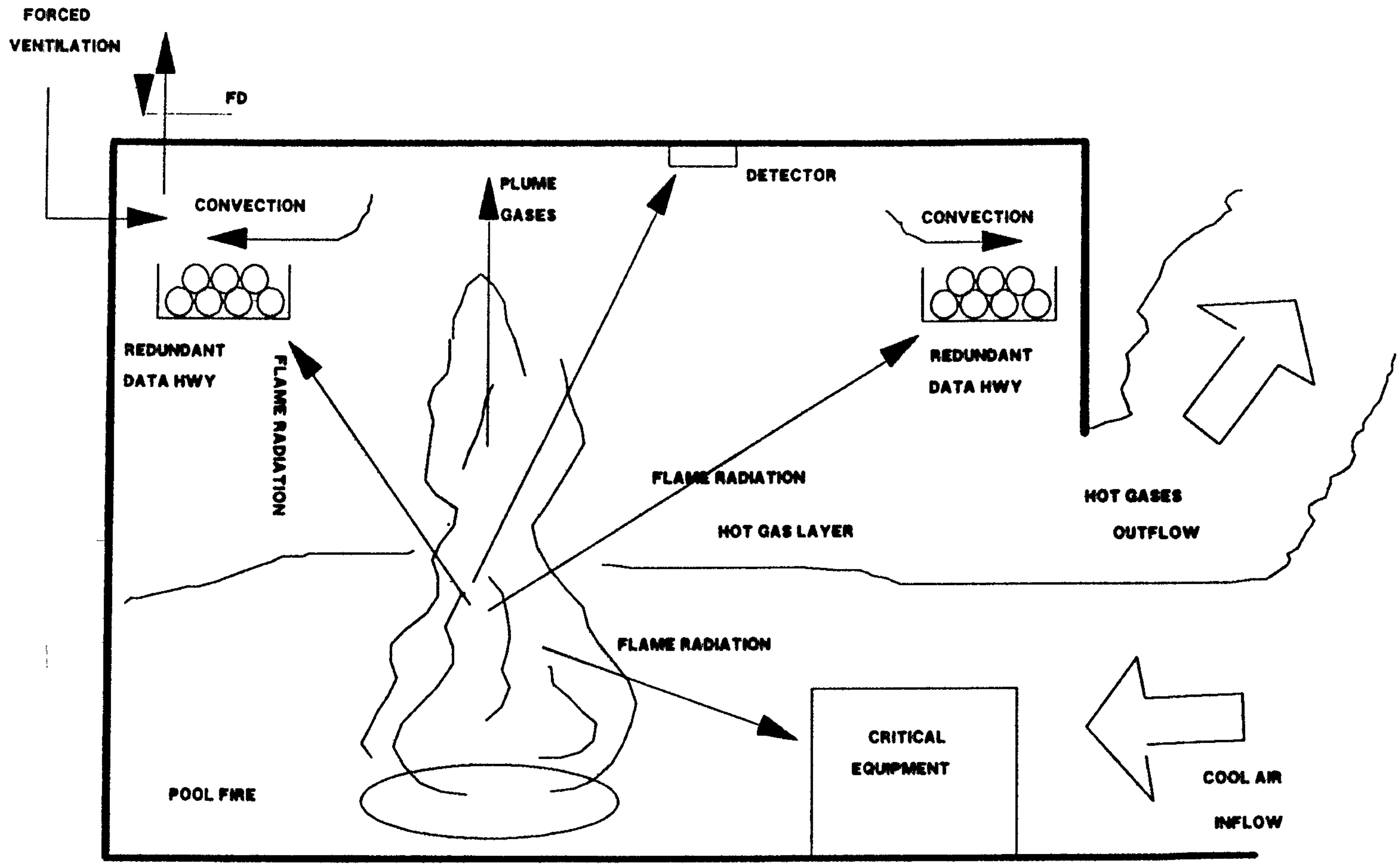

Figure 2-3 - Simplified Compartment Fire Model result of the air entrainment, the total upward mass flux in the plume continuously increases while its temperature decreases. When the plume gases impinge on the ceiling, they spread and form a relatively thin turbulent ceiling jet. As this hot jet moves radially outward, it transfers energy by convection, conduction, and radiation to the ceiling, causing its temperature to rise. This ceiling jet also sends fire signatures to the ceiling-mounted fire detectors and sprinkler nozzle heads.

When the ceiling jet is blocked by the room boundaries, it turns downward at the ceiling-wall juncture, thereby initiating a downward-directed wall jet. This wall jet is of higher temperature and lower density than the ambient air into which it is being driven. The wall jet, retarded by its relative negative buoyancy, turns upward and entrains an additional amount of cooler air from the lower region on its way up. Eventually, a relatively quiescent upper gas layer, called the hot gas layer, is formed below the continuing jet flow activity. Thus, stratified regions are formed as the fire grows, and the room is divided into several regions with distinct thermal boundaries. Objects within a hot gas layer will be subject to a similar degree of convective and radiative heat transfer.

Simple fire and heat transfer models and correlations were employed to predict the thermal environment as a function of time. The thermal response of various targets in the fire scenario was modeled to predict the amount of time required for a fire to damage or ignite critical equipment.

The fire growth, detection, and suppression processes are time-competing processes. As the fire heats up the equipment in the room, it also sends fire signatures to the fire detectors. The fire can cause damage before the detection system can respond, or before the suppression system can be actuated. These times can be summarized by two characteristic time factors, T_G and T_H, such that a component X can be defined to be damaged due to fire if $T_G < T_H$. The fire growth time, T_G, is defined as the time it takes for the fire to propagate to X and damage it. The hazard time, T_H, is defined as the total fire exposure time during which X can be damaged by the fire. The conditional frequency that X will be damaged, given that the fire occurs, can then be formulated as

$$Q_X = \text{Freq}\ \{T_G < T_H \mid \text{Fire}\} \tag{2-4}$$

where Freq $\{A|B\}$ denotes the frequency of occurrence of event A conditioned on the occurrence of event B.

Equation 2-4 simply says that the damage frequency of X, given that a fire has occurred, is equal to the frequency of the event having growth time smaller than the hazard time; i.e., the time to damage the component in a given magnitude of a fire is shorter than the time it takes to detect and suppress the fire.

The expression (as defined in Eq. 2-4) is usually modeled as an exponential process [Refs. 8, 10, and 11], such that:

$$Q_X = e^{-T_G/T_H} \tag{2-5}$$

The probabilistic distribution of Q_X is obtained by combining the distributions of T_G and T_H using the exponential model. For each critical location, the fire growth time, T_G, is estimated using the computer code COMPBRN III [Ref. 12]. If a fire-protection system is available in the location, the hazard time, T_H, is determined by the reaction of fire-protection systems such that

$$T_H = T_D + T_S \tag{2-6}$$

where T_D is the detection time; which is defined to include not only the time to acknowledge the presence of the fire, but also the time interval following acknowledgment but prior to initiation of suppression efforts. T_S is the suppression time; i.e., the time required to extinguish the fire after the actuation of the suppression systems (which could be a manual or an automatic system).

2.3.5 Fire-Induced Damage Probability

As described in Figure 2-2, each fire initiating event can have two scenarios that lead to equipment damage in that location. The conditional probability of equipment damage, P_X, due to a particular event, is the sum of the probability of occurrence of the two scenarios; i.e.,

$$P_X = (1 - U) * Q_{auto} + U * Q_{manual} \tag{2-7}$$

where

U = unavailability of the FPS.

Q_{auto} = probability of fire-induced damage calculated by Eq. 2-5 when the location is guarded by automatic FPS and the FPS fails to control the fire before damage.

Q_{manual} = probability of fire-induced damage calculated by Eq. 2-5 when manual suppression fails to control fire before damage.

2.3.6 Total Fire Risk

The unconditional probability of equipment damage due to a particular fire initiating event is then the product of the fire occurrence frequency and the conditional probability as assessed from the event tree. The probability of equipment damage in a critical location is the sum of the unconditional probability of all events developed to model the credible damage scenarios in that location. The total fire risk is equal to the sum of unconditional probabilities for all critical locations in the facility.

2.4 RISK MANAGEMENT

Risk management provides design confirmation and recommendations to reduce fire risk, if necessary. The design can be confirmed by either of the following:

(1) The risk of fire occurrence is acceptable so that protective measures are not necessary.

(2) The existing fire protection capabilities are adequate to prevent agent release due to fires.

The FRA utilizes the Risk Assessment Code (RAC) system to evaluate the risk associated with individual critical areas. The RACs are based on a combination of probability and severity, as delineated and approved in the CSDP Safety System Program Plan [Ref. 1]. For locations where the fire risk (RAC number) was found to be unacceptable, recommendations are provided to reduce such risk. Figure 2-4 describes the various hazards and control measures in fire risk management. The control measures are used to break down the "fire triangle" so that combustion cannot be sustained. In general, the likelihood of component damage can be reduced by :

(1) Slowing down the fire growth rate, e.g., by reducing combustible loading in rooms, or by installing fire barriers.

(2) Speeding the fire detection and suppression capabilities. Different types of fire detectors may be used to provide a faster response time, or to reduce the false alarm rate. Installation of automatic fire

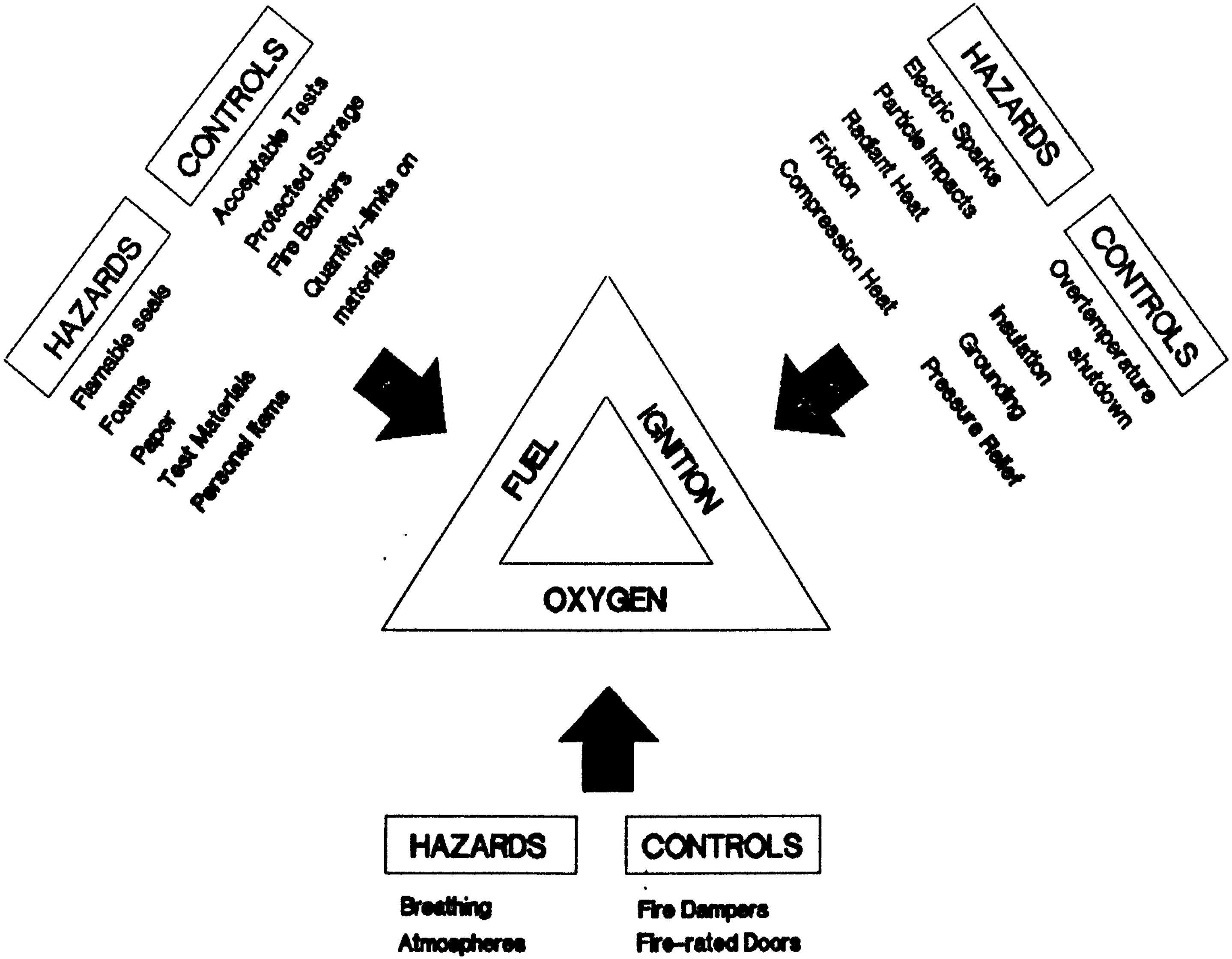

Figure 2-4 Hazards and Control Measures in Fire Risk Management

suppression systems may be necessary in locations where manual suppression capability is limited.

(3) The risk of common-cause failures due to fire can be reduced by increasing the redundancy of important equipment, and positioning the redundant components in independent areas so that single-mode and single-cause failure are virtually impossible.

3. FIRE RISK ASSESSMENT

3.1 SELECTION OF CRITICAL LOCATIONS AND COMPONENTS

There are two main objectives in selecting critical locations. The first objective is to ensure that all important locations are analyzed. This may lead to the consideration of a potentially large number of candidate locations. The second objective is to minimize the effort spent in quantifying the fire risk in unimportant locations. These two objectives are counteractive to each other and must be balanced in a meaningful FRA.

In order to account for all important locations and identify the critical locations systematically, the following information was obtained:

(1) The ESFs that are designed to safeguard against agent release from the demilitarization processes.
(2) The critical equipment that performs these ESFs.
(3) The locations of this critical equipment and its control and power cable routes.
(4) The fire areas that contain this critical equipment.

The critical locations were then selected based on the following criteria:

(1) The amount of critical equipment in a fire area.

(2) The presence of combustibles in the area.

(3) The potential of rapid fire growth, extinguishment delay, and equipment.

(4) Locations identified from previous studies (e.g., the SHA [Ref. 6]).

(5) The estimated frequency of fire occurrence and its consequences in these locations.

This screening process optimizes the effort in performing the FRA. However, the analysis does not indicate that other locations in the facility that are not in this list are absolutely free from fire risks. The critical locations chosen in the FRA are dominant to other areas in terms of the probability and consequences of fire occurrence.

The CSDP facility contains the basic process equipment and control systems necessary to disassemble, punch, and drain munitions and bulk items; to incinerate agent, other liquid, and solid waste; and to decontaminate munition bodies and other metal items. The facility also provides critical services to the personnel operating and maintaining the process equipment [Ref. 22]. ESFs are incorporated to safeguard these areas of operation by preventing propagation of agent from toxic areas to less-toxic or nontoxic areas. The functions identified as ESFs include the cascaded ventilation systems, containment protection, HVAC filtration, liquid agent removal, decontamination, control and power supply, and fire protection.

The ESFs, when needed, will be performed by the corresponding safety equipment. This safety equipment, coordinated with corresponding control and power supply units under both normal and off-normal conditions, is designed to prevent agent release to the nontoxic areas and to mitigate the consequences following agent-handling mishaps. Each of the ESFs may require one or more pieces of designated equipment to carry out its function. Table 3-1 shows the selected ESFs, critical components and their locations.

3.2 ESTIMATION OF FIRE OCCURRENCE FREQUENCY

The probability distributions for the fire-occurrence frequency at the critical locations were assessed by applying Bayes' Theorem. Data compiled from industrial plant experience (Table 2-1) are treated as evidence and modeled by the likelihood functions. The posterior distributions for the fire-occurrence frequency in each of the critical locations were developed using noninformative prior distributions. The posterior distributions were analyzed and modified with justification to closely reflect the difference between the analyzed facility design and the evidence.

3.3 AREA DESCRIPTION

An area description is based on reviewing the design drawings to identify the location of postulated ignition pilot fire, fuel elements, room openings, room dimensions, and locations of critical equipment. The area information is used for the COMPBRN III fire growth model.

3.4 FPS CHARACTERISTICS

Fire protection characteristics include the description of the fire-rated walls, the fire detection system, detector locations, zoning and spacing of the detection system, control panel type and location, and types of suppression systems. The information collected is used for the DETACT computer program to calculate the detector response time and the fire-suppression time.

3.5 FPS UNAVAILABILITY

The FPS unavailability refers to the FPS failure unavailable on demand. Fault-tree analysis is used to model the FPS. The analysis includes both the manual and automatic systems. The analysis includes the failure rate calculation of fire detection system, fire panels, and fire suppression system. The CAFTA computer workstation [Ref. 23] is used to perform the unavailability analysis. An example of an FPS fault tree is shown in Figure 3-1.

3.6 THERMAL-RESPONSE EVALUATION

The thermal response evaluation focuses mainly on the critical equipment fire-damage-time evaluation for a given fire. The thermal response of critical equipment is best estimated by the COMPBRN III computer code.

3.7 FIRE-HAZARD-TIME ASSESSMENT

Fire-hazard time is equal to the sum of the detector-response time and the fire-suppression time. The detector-response time is the time from the fire start to the time when detectors send signals to panels and/or fire warning systems. The length of detector response time depends on many factors: detector type, the type and size of fire, and the spacing of the detectors. The detector-response time is calculated by the DETACT computer code.

Table 3-1 - ESF, Critical Components and their Locations

Engineered Safety Functions	Critical Components	Location
1. Cascaded Ventilation System	Supply Air Blowers	Mechanical Equipment Room
		Air Handling Room
		Battery Room
		Switchgear Room
		Electrical Rooms
	Exhaust Air Blowers	HVAC Filter Areas
	Air Flow Isolation Dampers	Various Locations
	Instrument Air Compressors	Mechanical Equipment Room
2. Containment Protection	DPE Suits	Various Locations
	High Curb	Various Locations
	Sloped floor	Various Locations
	Enclosures	Various Locations
3. HVAC Filtration	Intake Filters	Mechanical Equipment Room
		Air Handling Room
		CON Filter Area
		Electrical Rooms
		Battery Room
		Switchgear Room
	Exhaust Filters	HVAC Filter Areas
	ACAMS	Monitor Houses
4. Liquid Agent Removal	Sumps	Various Locations
	Level alarms	Sumps
	Sump Pumps	Sumps
	Plant Air Compressors	Equipment Room
5. Decontamination	Decon Solution	Various Locations
6. Control and Power Supply	Instrument Cables	Various Locations
	Power Cables	Various Locations
	UPS Power Supply	Battery Room
7. Fire Protection	Fire Detectors	Various Locations
	Fire Control Panels	Various Locations
	Halon 1301	Halon Room
	Dry Chemical	Obs. Corridor 09-142
	Sprinkler System	UPA, CHB

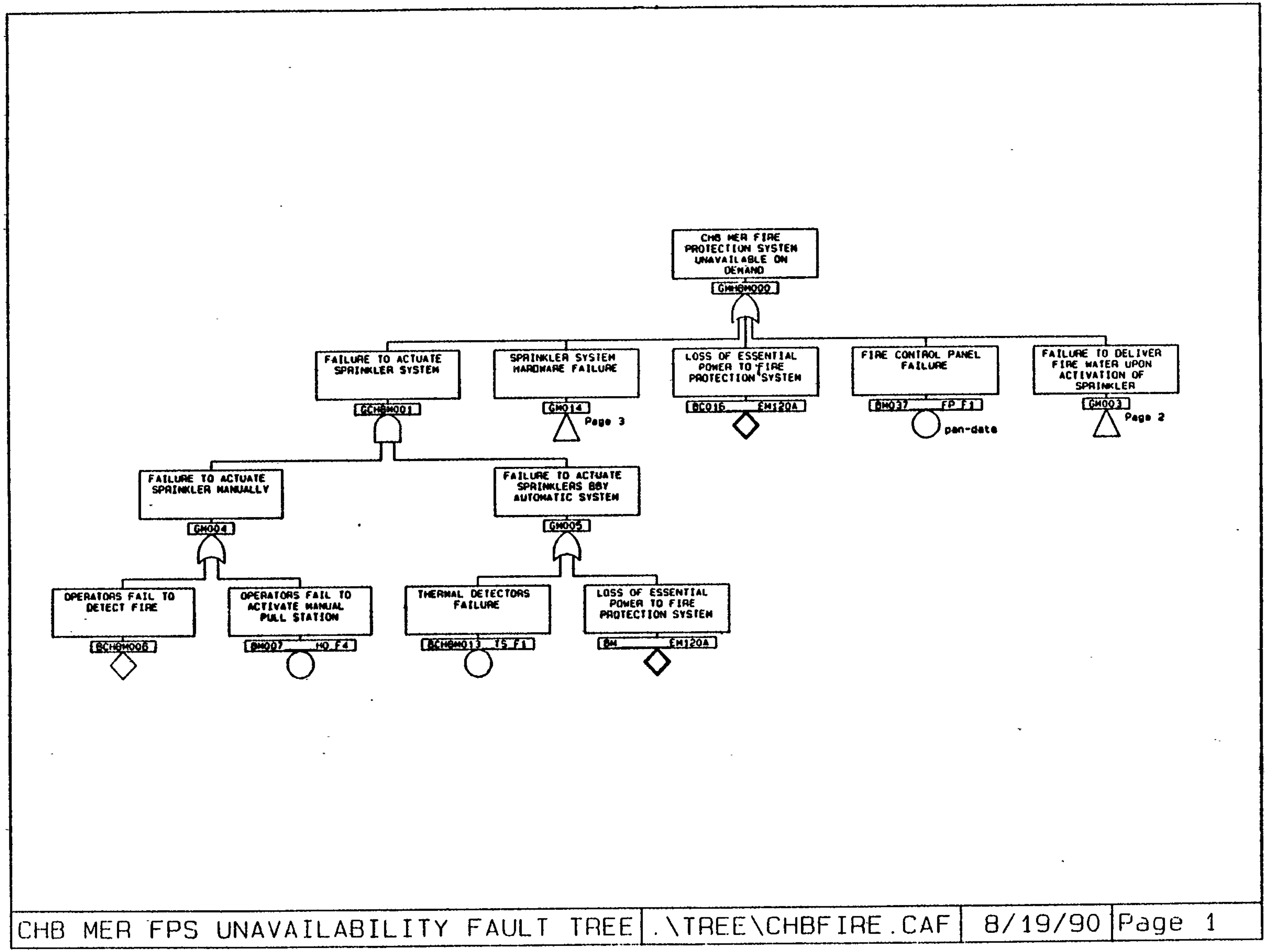

Figure 3-2 Fault Tree of a Fire Protection System

The fire-suppression time depends on the fire-suppression system design, the availability of the suppression system/equipment, the response of personnel, and accessibility of the area. Suppression time of the automatic FPS can be estimated by the available vendor data or engineering judgement. The manual suppression time will depend on the fire size, the experience of personnel, and availability of equipment. Engineering judgement is commonly used to estimate the manual suppression time.

3.8 FIRE-INDUCED-DAMAGE PROBABILITY

The fire-induced-damage probability, Q_X, of a piece of critical equipment x is calculated by Eq. 2-5. The calculated fire-induced-damage probability is the probability of either the automatic FPS or manual FPS depends on the area design.

3.9 UNCONDITIONAL FIRE RISK

The unconditional fire risk is the probability of fire damage to a piece of critical equipment based on all the fire scenarios in the area. The probability is the sum of the fire-induced-damage probability times the fire-occurrence frequency for the scenario. The total area fire risk is the sum of all critical equipment damage risks in the area. The total facility fire risk is the sum of all the area fire risks.

3.10 DISCUSSION AND INTERPRETATION

The fire risk calculations stated above show the parameters involved in the calculations, which in turn determine the fire risk of a critical equipment. The fire risk of the area is the sum of the fire risk of all the critical equipment in the area. If the fire risk is too high, risk management must be performed based on the variation of the crucial parameters. The fire risk analyst must interpret the results to FPS designers to develop an alternative FPS design. If the design change is not feasible, stringent operating procedures must be incorporated in the plant standing operating procedures to reduce the fire-occurrence frequency and to reduce the fire-suppression time.

4. CONCLUSION

The fire risk of a CSDP facility has been quantified by applying the FRA methodology described in Section 2. The methodology combines the use of state-of-the-art computer codes, engineering judgment, relevant industrial experience, and numerical analysis techniques to evaluate the unconditional probability of fire damages in various critical locations of the facility.

As discussed in Subsection 2.4, the results of the assessment confirm whether the design is within the acceptable safety margins by comparing the risk with the RACs. In locations where the fire risks are found to be unacceptable, design recommendations are provided to reduce such risk based on FRA and FPS designer discussion. These recommendations were developed primarily based on the dominant factors in the FRA to reduce the fire hazard time (detection and suppression), increase the fire growth time, prevent fire propagation, and reduce fire occurrence frequency. The fire risks of the facility were re-evaluated based on the FRA recommendations.

During the course of FRA, it was found that a small fire is as important as big fire. This is because small fires have high occurrency rates and they can damage critical equipment before or without actuating the FPS. The ESFs are engineering-designed components to protect the facility from agent release, major equipment damage, and personal injury.

The quantitative assessment of the recommended FRA provides a basis for fire-risk management. The results of assessed risk at different locations can be used as priority scales to determine where the risk management effort should be focused. This is a key concept of risk management.

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